CHAPTER 6. ENGINEERING ANALYSIS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 6. ENGINEERING ANALYSIS

6.1 INTRODUCTION

The purpose of the engineering analysis is to estimate the energy savings potential according to the DOE test procedure from increased equipment efficiency levels, and the incremental equipment and installation cost of achieving those levels, compared to the baseline models in each product class. The engineering analysis estimates the payback period for each of the design options in order for DOE to address the legally required "rebuttable" payback consideration. The Department uses the costs developed in the engineering analysis in the life-cycle cost analysis.

The baseline models for each product class are the starting point for analyzing technologies that provide energy-efficiency improvements. The Department defined a baseline model as an appliance having the simplest, most cost-effective features and technologies while just meeting the current minimum standard. The Department defined baseline models for each of the product classes with sales volumes greater than 100,000 per year.

To explore how manufacturers would likely design products to meet a minimum standard, and to thoroughly understand the relationships between different equipment configurations and efficiency, the Department considered various design options that could meet a given efficiency level.

The Department estimated inputs to determine payback periods, which represent the time required for the increase in average total installed equipment cost to be offset by annual average operating cost savings. The Department estimated total installed cost to the consumer through an analysis of manufacturer costs, markups, and installation costs; annual average operating costs are estimated by calculating energy consumption using the DOE test procedure, applying average energy prices, and adding annual average maintenance costs.

6.2 PRODUCT CLASSES CONSIDERED

The Framework Document[1] outlined 13 classes of furnaces and boilers:

- Gas Furnaces (Weatherized and Non-Weatherized);
- Oil-Fired Furnaces (Weatherized and Non-Weatherized);
- Mobile Home Furnaces (Gas-Fired and Oil-Fired);
- Hot-Water Boilers (Gas-Fired and Oil-Fired);
- Steam Boilers (Gas-Fired and Oil-Fired);
- Electric furnaces; and

- Combination Space/Water-Heating Appliances (Gas-Fired and Oil-Fired).

Based on the market assessment and stakeholder comments, the Department divided these product classes into four categories, based primarily on shipment volume.

The first category consists of the most widely used product class, non-weatherized gas furnaces, which have annual shipments of more than 2.5 million units. The Department's analyses considered this product class in depth.

The second category consists of those classes that typically have shipments of more than 100,000 per year: (1) weatherized gas furnaces, (2) mobile home gas furnaces, (3) non-weatherized oil-fired furnaces, (4) hot-water gas boilers, and (5) hot-water oil-fired boilers. The analysis of these product classes was similar to that of the first category, but DOE included less detail on electricity savings and considered a smaller number of design options.

The third category includes the classes with a low level of shipments: steam gas boilers and steam oil-fired boilers. For these classes, DOE applied the results of the analyses of the hot-water boiler product classes.

The Department did not conduct analyses on weatherized oil-fired furnaces, mobile home oil-fired furnaces, electric furnaces, and combination appliances. The first two classes have very low (essentially zero) shipments. The Department did not consider electric furnaces because it did not identify any significant energy savings potential. (The heating element of electric-resistance furnaces is close to 100 percent efficient.) The Department did not include combination appliances in the current analysis, since a test procedure for this product class is not in place and DOE has not yet made a decision whether to regulate this product class.

6.3 IDENTIFICATION OF BASELINE MODELS

The Department defined baseline units as appliances with commonly available features and technologies that just meet the current minimum efficiency standard. For each of the product classes in the first and second categories described above, the Department identified a baseline model. Itconsidered technical descriptions of the covered equipment, definitions of the product classes as described in the framework document, results of the market assessment, and suggestions from stakeholders. Table 6.3.1 summarizes the main features of the baseline models.

Table 6.3.1 Features of Baseline Models by Product Class

Product Class	Input Capacity (Btu/hr)	AFUE (%)	Configuration	Heat Exchanger Type	Ignition	Draft
Non-Weatherized Gas Furnaces	75000	78	Upflow	Clam Shell/Tubular	Hot Surface	Induced
Weatherized Gas Furnaces	75000	78	Horizontal	Clam Shell/Tubular	Hot Surface	Induced
Mobile Home Gas Furnaces	70000	75	Downflow	Drum	Standing Pilot	Natural
Non-Weatherized Oil-Fired Furnaces	105000	78	Upflow	Drum	Intermittent Ignition	Forced
Gas Hot-Water Boilers	105000	80	N/A	Sectional, Dry-base, Cast-iron	Standing Pilot	Natural
Oil-Fired Hot-Water Boilers	140000	80	N/A	Sectional, Wet-base, Cast-iron	Intermittent Ignition	Forced

In addition to the above features, the baseline models have a blower or pump driven by a standard permanent split capacitor (PSC) induction motor.

6.4 MANUFACTURING COST ANALYSIS

After assessing the available methods and taking stakeholder comments into account, the Department used reverse engineering of existing products to estimate the manufacturing cost of the baseline model and the considered design options. The reverse-engineering approach is a cost assessment based on a detailed bill of materials (BOM) for the various models. Appendix 6.1 describes the technical aspects of the approach as applied to residential furnaces and boilers.

The Department applied the reverse-engineering approach in conjunction with a review of relevant literature, computer simulation, and other analytical techniques. In some cases, DOE adopted industry-supplied data. Throughout the analysis period, the Department provided Gas Appliance Manufacturers Association (GAMA), manufacturers, and other stakeholders several opportunities to review and comment on the equipment cost estimates to ensure accuracy and completeness. The Department considered these comments in its analysis.

In estimating production costs for each candidate efficiency level above the baseline model, DOE considered several design options that could be used to reach a given annual fuel utilization efficiency (AFUE) level. The Department also considered additional options that provide electricity savings. The Department determined the efficiency levels corresponding to various design option combinations using DOE engineering calculations and manufacturer data submittals.

The Department took the following steps in establishing manufacturing costs as a function of fuel efficiency:

- Generate BOMs for products at different efficiency levels using teardown analysis (disassembly of units) and numerical simulations;

- Enter BOMs into a cost model, incorporating assumptions obtained through available industry data, internal expertise, visits to manufacturers, and stakeholders' input;

- Perform sensitivity analysis and cost-per-pound estimates; and

- Generate cost-efficiency data for each product class.

The Department further divided each of these steps into several sub-tasks, as described in the following sections.

Prior to its decision not to regulate furnace and boiler electricity use (see section 1.3 of Chapter 1), DOE assessed the manufacturing cost of the electricity-efficiency design options that passed the screening analysis. The results are given in Appendix 8.5 for informational purposes.

6.4.1 Generation of Bills of Materials

A BOM is a list of all the components that comprise a given appliance. In the BOM, the Department lists each component and provides a detailed description of its dimensions, function, and material, and information about its manufacturing and assembly process.

The Department generated the BOMs by examining and disassembling (through teardown analysis) some current-market units and/or simulating design options using numerical models and creating "hypothetical" units that it costed as if they were real units.

6.4.1.1 Teardown Approach

In the context of this analysis, the terms "reverse engineering" and "teardown analysis" solely describe the estimation of production costs by examining actual equipment or designs. The availability of a large number of residential products, with a wide range of efficiency, allowed DOE to consider most potential design options in a reverse-engineering approach, to establish an accurate estimate for production costs. The Department purchased and disassembled by hand the selected units, and measured, weighed, and analyzed each part. Additionally, DOE studied and reconstructed all the steps of the manufacturing processes to complete the teardown analysis. The result was a detailed BOM that DOE used as an input to the cost model.

Selection of Units. During the process of selecting units for teardown, DOE considered three main questions: (1) What efficiency levels should be captured in the teardown analysis? (2) Are there units on the market that capture all potential efficiency levels and design options? (3) Which of the available units are most representative?

In responding to the preceding questions, DOE adopted the following criteria for selecting units for the teardown analysis:

- The selected products should span the full range of efficiency levels under consideration;
- Within each product class, the selected products should come from the same manufacturer and be within the same product series;
- The selected products should come from a manufacturer that has a large market share in that product class; and
- The selected products should have non-efficiency-related features that are the same as, or similar to, features of other products in the same class and at the same efficiency level.

Additional criteria for selecting the teardown units included the following:

- The input capacities were as close as possible to the baseline model capacity for each product class;
- The units were manufactured in considerable volume and commonly available; and
- The units had the most popular features and average energy consumption values.

The Department focused heavily on non-weatherized gas-fired furnaces and, therefore, selected half of the teardown units within that class. The units selected for teardown included five non-weatherized gas-fired furnaces, one mobile home furnace, one oil-fired furnace, one weatherized gas-fired furnace, and two gas-fired hot-water boilers.

Non-Weatherized Gas-Fired Furnaces. Non-weatherized gas-fired furnaces represent the vast majority of the furnace and boiler market. Therefore, DOE's teardown analysis included five models that are representative of the efficiency levels and design options available for these types of furnaces on the market. Residential furnace manufacturers typically offer products in three distinct efficiency ranges: non-condensing (between 78 percent and 80 percent AFUE, with ~75 percent of the market at 80 percent AFUE), near-condensing (between 81 percent and 83 percent AFUE, ~1 percent of the market), and condensing (higher than 88 percent AFUE, ~24 percent of the market). When possible, DOE selected the least-efficient and the most-efficient units in a given efficiency range.

Thus, DOE selected three units in the non-condensing and near-condensing ranges (low, medium, and high efficiency) and two units in the condensing range (low and high efficiency).

In order to study the potential effects of design differences (such as tubular-versus-clamshell heat exchangers), DOE selected models made by two major manufacturers that represent significantly different designs. In this document, the Department refers to these two models as “Base Design A” and “Base Design B.”

Weatherized Gas Furnaces. Manufacturers of weatherized gas furnaces offer products between 78 percent and 82.7 percent AFUE. The Department picked one representative unit in this range. Manufacturers typically sell weatherized furnaces as “packaged” units, which means they include a furnace and an air conditioner in the same box. Contractors typically install packaged units outside of a residence. The packaged teardown unit that DOE selected had a three-ton air-conditioner capacity, which appears to be the most representative cooling capacity.

Mobile Home Furnaces. Mobile home furnace manufacturers offer products at the following efficiency levels: 75 percent, 80 percent, and 90 percent AFUE.

For this analysis, DOE used a baseline model efficiency level because the market currently presents a very low degree of design variability. The design differences between a 75 percent-AFUE unit and a higher-efficiency unit are very limited (i.e., manufacturers incorporate electronic ignition, baffles and draft induced to achieve 80 percent AFUE, and a secondary heat exchanger to achieve 90 percent), and DOE could effectively determine the costs of these components without performing a teardown for each efficiency level.

Oil-Fired Furnaces. Manufacturers of oil-fired furnaces typically offer products between 78 percent and 86 percent AFUE. Very few units are at the baseline model efficiency level (i.e., 78 percent AFUE), and DOE did not find a unit that is considered representative at efficiency levels lower than 81 percent. Therefore, DOE decided to analyze one unit at an intermediate level, rather than at the baseline model level.

Gas Hot-Water Boilers. One of the major differences between gas-fired hot-water boilers and gas-fired furnaces is that, for boilers, the transition between non-condensing and condensing appliances is continuous and there is no gap in the distribution of efficiency values on the market. Boiler models are available at virtually all efficiency levels between 80 percent and 98 percent AFUE.

The Department set the efficiency value of 84 percent AFUE as the highest efficiency level for performing teardowns of gas hot-water boilers because, at efficiency values higher than 84 percent, appliances present certain physical and operational characteristics (such as direct vent or warm-up loop) that are not representative of the market. Therefore, DOE chose two units for teardown that would bracket the representative efficiency range (80–84 percent AFUE).

Condensing boilers are rare, and DOE selected none of them for the teardown analysis.

Boilers can be made of cast iron, steel, copper, or aluminum. Since cast-iron sectional boilers are the most popular, DOE selected these for the teardown analysis.

Oil-Fired Hot-Water Boilers. Oil-fired boilers represent a small portion of the furnace and boiler market. For this reason, DOE did not tear down an oil-fired boiler. To estimate manufacturing costs of oil-fired hot-water boilers, DOE used available information from other product classes, taking advantage of similarities between gas- and oil-fired hot-water boiler heat exchangers, and between oil-fired furnace and boiler burners.

6.4.1.2 Modeling Approach

The sample units used in the teardown analysis do not include all possible efficiency levels or design options of each product class. Thus, DOE used a modeling approach to create BOMs for additional efficiency levels and design options. First, DOE identified efficiency levels not covered in the teardown analysis (Table 6.4.1). The Department then selected the design options most likely to be implemented by manufacturers, identified possible design modifications of existing units, and created a written description of hypothetical units.

Table 6.4.1 Gaps in Efficiency Levels of Units Selected for Teardown

Product Class	Selected Units	Gaps
Non-weatherized Gas Furnaces—*Base Design A*	**Non-condensing range**: 1 average efficiency and 1 high efficiency **Condensing range:** None	Baseline model efficiency - units in the non-condensing range, units in the condensing range, units with modulation
Non-weatherized Gas Furnaces—*Base Design B*	**Non-condensing range**: 1 baseline model efficiency and **Condensing range:** 1 low efficiency and 1 high efficiency	Higher-efficiency units in the non-condensing range, average-efficiency units in the condensing range, units with modulation
Mobile Home Gas Furnaces	**Non-condensing range:** 1 baseline model efficiency	Higher-efficiency units in the non-condensing range, condensing units
Hot-Water Gas Boiler	**Non-condensing range**: 1 baseline model efficiency and 1 higher efficiency	Average-efficiency units in the non-condensing range, condensing units
Non-weatherized Oil-Fired Furnaces	1 baseline model efficiency	Higher-efficiency units
Oil-fired Hot Water Boiler	None	Entire product class

Selection of Design Options and Efficiency Levels. The following section describes the selection of design options and efficiency levels for all product classes.

Non-weatherized Gas Furnaces. A report from the Gas Research Institute (GRI)[2] provided the background information DOE used as a basis to select design options for non-condensing, non-weatherized gas furnaces. The GRI report considered a large universe of design options, and assigned a cost and efficiency improvement to each design option. Although DOE did not use this cost information in the remainder of its analysis, it used these data to select design options. Table 6.4.2 ranks the options on the basis of cost-per-one-percent of AFUE increase.

Table 6.4.2 Ranking of Design Options

Design Option	GRI 1994 Cost (Without Installation)	AFUE Increase	$/% AFUE Increase
Improved Heat-Transfer Coefficient	$14	1.7%	8.2
Increased Heat-Exchanger Area	$40	1.7%	23.5
Derating	$41	1.7%	24
High-Mass Heat Exchanger	$71	0.8%	89
Advanced Burner	$66	0.7%	94
Flue-Gas Recirculation	$35	0.3%	117
Improved Insulation	$39	0.2%	195
Increased Insulation	$60	0.3%	200
Forced Draft	$20	none	-

Three options—improved heat-transfer coefficient, increased heat-exchanger area, and derating—are the most cost-effective approaches for increasing AFUE. Among these three options, increased heat-exchanger area and derating are virtually identical, since they rely on the same concept (increasing the ratio of heat-exchanger area to burner input). Therefore, DOE focused on two design options for non-weatherized gas furnaces: improved heat-transfer coefficient and increased heat-exchanger area. Another design option, forced-draft system, passed the screening criteria, but the Department did not use this option in its analysis, as the GRI study indicates that forced-draft combustion systems do not appear to offer efficiency improvements comparable to the induced draft system.

The Department further considered the heat-exchanger design types. For the non-condensing range, DOE considered two different heat-exchanger design types: clamshell and tubular, indicated as "base design A" and "base design B," respectively. Since the designs present only minor cost differences, and to prevent any possible disclosure of confidential or proprietary information, DOE aggregated their costs.

The majority of the manufacturers of condensing furnaces and boilers use secondary stainless-steel heat exchangers. Therefore, DOE considered condensing furnaces and boilers with stainless-steel heat exchangers in estimating the cost of a minimum-efficiency condensing unit (90 percent AFUE). To reach higher efficiency in the condensing range, DOE considered increased heat-exchanger area, instead of an improved heat-transfer coefficient, since the latter did not seem to provide any economic advantage (based on pressure-drop considerations and observation of available products).

The Department also considered modulation as a design option. While modulating furnaces are typically known for delivering superior comfort, the modulation feature can also provide an AFUE improvement. GRI did numerical simulations to model several furnaces, in which it controlled for the burner input rate, excess air fraction, and circulating air-flow rate.[2] These simulations showed AFUE improvements ranging from 2.9 percent to 3.2 percent due to modulation with two-stage electronic controls. The report indicates that achieving this level of improvement requires a higher-efficiency electronically commutated motor (ECM) blower, control of excess air, and adjusting the circulating air flow.

Another, less-expensive design approach currently in the market uses a multiple-tap, multiple-speed PSC blower motor; a two-stage gas valve; and a multiple-tap, two-speed PSC inducer motor to obtain two-stage modulation operation. For this latter "two-stage modulation" approach, DOE estimated that an additional $23 would need to be added to the production cost of the furnace to account for the component changes (at high production volumes).

In the GAMA directory, for many pairs of non-modulating and modulating furnaces with similar families and capacities, manufacturers report AFUE rating differences ranging from 0 percent to 2.5 percent AFUE (the modulating furnaces being the more efficient). To estimate the cost of a modulating furnace at any given AFUE level, DOE added $23 to the production cost of a furnace at the next-lower efficiency level (i.e., one AFUE point less). For example, DOE determined the cost of an 81 percent AFUE modulating furnace by adding the cost of the modulation changes to the least-expensive 80 percent AFUE non-modulating furnace.

The Department selected efficiency levels up to 83 percent AFUE for the near-condensing range, because there are products available that approach 83 percent AFUE (i.e., 82.7 percent AFUE). DOE recognizes that, with these units, improperly installed or inappropriate venting systems may pose potential safety hazards—this was mentioned by several stakeholders during the May 8, 2002, DOE public workshop on venting. The Department did not analyze near-condensing furnaces above 83 percent AFUE, since these have similar safety and cost issues as the 83 percent AFUE furnace.

For the condensing range, DOE considered efficiency levels between 90 percent and 96 percent AFUE, which is very close to the highest-efficiency commercially available unit.

Weatherized Gas Furnaces. The Department considered insulation as an additional design option for weatherized gas furnaces, since these units are located outdoors, and jacket losses can significantly affect AFUE. For efficiency levels, DOE considered up to 83 percent AFUE, based on product availability.

Mobile Home Gas Furnaces. For mobile home gas furnaces, DOE investigated a combination of design options. From product literature, DOE learned that, to move from 75 percent to 80 percent AFUE, manufacturers use electronic ignition, and improve the heat transfer coefficient by using baffles, and add a draft inducer. Therefore, DOE considered these options to increase efficiency from 75 percent to 80 percent AFUE.

Because products for mobile homes are not commercially available between 80 percent and 82 percent AFUE, DOE relied on its analysis for non-weatherized furnaces and selected the least-expensive design option for that product class (i.e., increased heat-exchanger area).

The Department selected efficiency levels between 75 percent and 82 percent AFUE in the non-condensing range and one level (90 percent AFUE) in the condensing range. To estimate the cost for the 90 percent AFUE level, DOE relied on an alternative approach, described in section 6.4.2.

Oil-Fired Furnaces. For oil-fired furnaces, DOE considered only the increased heat-exchanger-area design approach. This is because improving the heat-transfer coefficient is not a common practice in the oil-fired furnace industry, due to potential smoke production. The Department considered oil-fired furnaces with efficiencies up to 85 percent AFUE.

Gas Hot-Water Boilers. Review of manufacturers' product literature and analysis of the teardown units show that manufacturers commonly improve efficiency in the non-condensing range by incorporating either electronic ignition or an improved heat-transfer coefficient (baffles), or a combination of the two. The Department also considered two-stage modulation, along with induced draft, as a possible option. Based on the models available on the market, DOE analyzed gas boilers up to 99 percent AFUE. However, to estimate the cost for condensing gas boilers, DOE relied on an alternative approach, described in section 6.4.2.

Oil-Fired Hot-Water Boilers. The only design option approach DOE considered for oil-fired boilers was increased heat-exchanger area, since improving the heat transfer coefficient is not a common practice in the oil-fired boiler industry due to smoke issues. The Department considered efficiency levels up to 95 percent AFUE.

Build "Hypothetical" Units and Create Bill of Materials. This phase of the analysis consisted of modifying the design of existing units to produce hypothetical units that perform at the desired efficiency levels. This process involved applying the selected design modifications to representative models, for which DOE obtained information through the teardown analysis or through product literature, to "build" hypothetical units.

For gas furnaces, the Department used the *FURNACE* simulation model, provided by the Gas Technology Institute (GTI), to predict AFUE increases corresponding to the increases in heat-exchanger area. The model accepts descriptions of modified units as an input and provides efficiency levels for each input.

For gas boilers, DOE examined the existing product literature and analyzed the efficiency improvements associated with the selected design options; it interpolated the data when information was not available. In this product class, electronic ignition and/or addition of baffles to the heat exchanger are common ways to increase efficiency by 2 percent AFUE (each). Since manufacturers equip more units with electronic ignition at higher efficiencies, DOE assumed that a high fraction of the boilers at a high AFUE level are equipped with electronic ignition, and a smaller fraction are equipped with a set of baffles. For intermediate-efficiency levels, DOE linearly interpolated the cost of materials of a higher- and a lower-efficiency unit.

For mobile home furnaces and oil-fired equipment, the Department applied heat- exchanger scaling factors derived from thermodynamic or empirical considerations to estimate the increase in the heat-exchanger area.

After the Department "built" the units, it disassembled and costed them as if they were real units.

6.4.2 Approach for Condensing Boilers and Mobile Home Furnaces

Even after completion of both the teardown analysis on representative units and the numerical simulations, the Department still needed information for condensing boilers (both gas- and oil-fired) and condensing mobile home furnaces. For these categories, DOE identified possible design options but did not have a methodology or a simulation tool in place to estimate the production costs. Therefore, the Department used a cost-per-pound estimation methodology to estimate production costs for these products sold in low volumes. It relied on the following five steps:

1. Examine the cost per pound and the cost-per-pound trend of non-weatherized gas furnaces (the most comprehensive information is available for this product class).
2. Find the cost per pound at other efficiency levels within the analyzed product class.
3. Determine typical shipping weights of units available on the market for the analyzed case (e.g., 90 percent-AFUE mobile home furnace).
4. Create a preliminary estimate, assuming that similar designs and materials are used across the range of manufacturers.
5. Modify preliminary estimate to reflect other factors (e.g., all-stainless design).

6.4.3 Cost Model and Definitions

The Department based the cost model on production activities, and divided factory costs into the following subsets:

Material*:* Direct and Indirect Materials.

Labor*:* Fabrication, Assembly, Indirect, and Overhead (Burdened) Labor.

Overhead*:* Equipment Depreciation, Tooling Depreciation, Building Depreciation, Utilities, Equipment Maintenance, Rework.

Since there are a large variety of accounting systems and methods in use to monitor costs, DOE defines the above terms as follows:

Direct Material: Purchased parts (out–sourced) plus manufactured parts (made in–house).

Indirect Material: Material used during manufacturing (e.g. welding rods, adhesive), but not normally considered part of the product.

Fabrication Labor: Labor associated with in-house piece manufacturing.

Assembly Labor: Labor associated with final assembly and sub-assemblies.

Equipment and Plant Depreciation: Money allocated to pay for initial equipment installation and replacement as the production equipment wears out.

Tooling Depreciation: Cost for initial tooling (including non-recurring engineering and debugging of the tools) and tooling replacement as it wears out.

Building Depreciation: Money allocated to pay for the building space.

Utilities: Electricity, gas, phones, etc.

Equipment Maintenance: Money spent on yearly maintenance, both materials and labor.

Indirect Labor: Plant labor that scales directly, based on the number of direct workers (assembly + fabrication). Includes supervisors, technicians, and manufacturing engineering support.

Overhead labor: Fixed plant labor that is spread over a number of product lines and includes accounting, quality control, shipping, receiving, floor supervisors, plant managers, office administration, and environmental health and safety. Not included are: R&D, corporate management, general administration, and maintenance labor.

Rework: Labor and materials associated with correction of in-plant manufacturing defects.

The Department input the cost data from all the BOMs, whether they were obtained through teardowns or numerical simulations, into the cost model, which makes use of specific assumptions to provide cost estimates. The next sections describe the set of assumptions DOE used during this analysis.

6.4.3.1 Outsourcing

The Department characterized parts based on whether manufacturers purchase them from outside suppliers or fabricate them in-house. For purchased parts, DOE estimated the purchase price. For fabricated parts, DOE estimated the price of intermediate materials (e.g., tube, sheet metal) and the cost of transforming them into finished parts. Whenever possible, DOE obtained price quotes directly from suppliers of the manufacturers of the units being analyzed. For higher-efficiency equipment, DOE assumed that the component purchase volume was the same as the current baseline model. This assumption may have resulted in lower component prices than manufacturers currently pay. Most of the manufacturers carry out manufacturing operations in-house, as summarized in Table 6.4.3.

Table 6.4.3 Cost Model Outsourcing Assumptions

Process	Sub–Process	In-House	Outsourced
Tube Forming	Tube Cut	✔	
	Tube Bend	✔	
	Roll Form	✔	
	Tube Coil	✔	
Sheet Metal	Stamping	✔	
	Press Brake	✔	
	Blanking	✔	
	Turret Punch	✔	
	Plasma Cut	✔	
Welding	Seam Welding	✔	
	Spot Welding	✔	
Machining	Machining Center	✔	
Finishing	Paint	✔	
Assembly	Adhesive Bonding	✔	
	ToxLox	✔	
	Press Fit	✔	
	Fixture	✔	
	Miscellaneous Assembly Operation	✔	
Final Assembly	Packaging	✔	
	Quality Assurance	✔	
Molding	Injection Mold		✔
Casting	Sand Cast		✔

Similarly, the Department made assumptions about which components manufacturers purchase from external suppliers (Table 6.4.4).

Table 6.4.4 Cost Model Assumptions on Outsourced Components

Sub-Assembly	Outsourced Components
Blower	Motor - Wheel - Capacitor
Inducer	Motor - Wheel - Capacitor
Casing	Insulation
Circulator	Circulator Pump - Motor
Electrical/Controls	Control Board - Switches - Capacitors - Tranformers - Relays - Connectors
Exterior Components	Vent Dampers
Filter	Filter

Fuel Control	Gas Valve Assembly - Igniter - Manifold - Flame Sensor
Burner	Orifices - Oil Burner
Heat Exchangers	Refractory, Cast Iron Section
Packaging	Pallet - Box

6.4.3.2 Greenfield Facility Specifications

To estimate production costs in the industry, the Department created a prototypical "greenfield" production facility. In this exercise, DOE theoretically built a new facility from the ground up, for the sole purpose of producing the equipment under analysis. This simplification suppressed differences among manufacturers and focused on generic aspects in plant and process that were related to efficiency. The results may, therefore, overestimate or underestimate the production costs of a particular manufacturer. However, since they were calibrated to aggregate industry data, they should be representative of the industry as a whole.

The Department based the assumptions for the generic greenfield facility on manufacturer interviews and analysis of common industry practices, as reported in Tables 6.4.5 and 6.4.6.

Table 6.4.5 Greenfield Facility Specifications

	Greenfield Facility Specifications
Production Days / Year	250
Fabrication Shifts / Day	2
Assembly Shifts / Day	1
Hours per Shift	8
Press Lot Size per Day	1
Worker Downtime	20%
Equipment Downtime	10%
Actual/Designed Production Capacity Ratio	0.7
Assembly Line	Dedicated

Table 6.4.6 Greenfield Facility Production Cost Assumptions

	Greenfield Facility Production Cost Assumptions
Capital Recovery Rate	15%
Building Depreciation Period	25 Years
Equipment Depreciation Period	7–20 Years (depending on which product class)
Fringe Benefits Ratio	40%
Direct Labor Cost Rate	14 $/hour (based on US assembly worker average)
Direct/Indirect Labor Cost Ratio	50% of direct labor
Utility Cost	3% of factory cost
Maintenance Cost	3% of depreciation
Freight In	3% of materials cost
Rework Rate	8% of manufactured material, fab labor and assembly labor
Assembly Factor	1.5 (buffer for assembly-worker speed variation)
Building Cost	$120/square foot

6.4.3.3 Production Volumes

Production volume—the number of units produced annually within a product series and using similar parts—is a very important variable in estimating manufacturing costs. The Department allocated fixed costs to a product on the basis of production volumes.

Using the shipments data that GAMA provided,[3] as well as assumptions about market shares for each manufacturer in each class, DOE made initial estimates of the annual production volume for each manufacturer's product family. Individual manufacturers and GAMA reviewed these estimates, and the Department subsequently modified the estimates to incorporate their comments and information. Note that these production volumes dictated how DOE assigned tooling costs on a per-unit basis, so the estimates applied to product families, not to sales of an individual product in the product line. Purchasing power for components also follows these production volumes, except in cases where the purchased part in question is a commodity item (in-shot burners, for example). In such a case, DOE assumed higher production volumes.

Table 6.4.7 itemizes the assumed typical production volumes for each of the product classes under consideration.

Table 6.4.7 Annual Production Volume Assumptions

Product Class	Production Volume
Non-Weatherized Gas-Fired Furnaces	100,000
Weatherized Gas-Fired Furnaces	100,000
Mobile Home Gas-Fired Furnaces	100,000
Gas-Fired Hot-Water Boilers	30,000
Non-Weatherized Oil-Fired Furnaces	5,000
Oil-Fired Hot-Water Boilers	30,000

Finally, DOE wanted to capture the production costs manufacturers would incur if a standard were set at a given efficiency level. The Department held the production volume constant for each considered efficiency level.

6.4.3.4 Generating Production-Cost Results

The Department input all of the data it had gathered into Microsoft Excel workbooks—one for each product class—that estimate the cost of fabricating the components and assembling the equipment. The workbooks contain proprietary and confidential information and are not publicly available, but the aggregated results are available to the public in the form of spreadsheets and are posted on the DOE web site. The completed spreadsheets generated the production costs for the models evaluated.

6.4.4 Sensitivity Analysis

Manufacturing cost-efficiency correlations do not portray the uncertainty and variability in the assumptions. Uncertainty arises when the precise model parameters cannot be determined. Variability arises when the precise value is known but it varies among manufacturers, suppliers, or processes.

To quantify the uncertainty and variability in the production-cost estimates, DOE used Crystal Ball Pro to run Monte Carlo simulation analyses. This kind of sensitivity analysis identifies which variables have the largest effect on cost estimates and on the accuracy of cost predictions. The Department performed the sensitivity analysis in five sequential steps:

1. Identify variable ranges,
2. Perform Monte-Carlo simulations,
3. Rank variables in order of influence on the cost results,
4. Refine assumptions (variable ranges), and
5. Perform additional simulations.

In the first step, DOE assigned to each variable a degree of uncertainty. To make these assignments, DOE used industry-accepted rules, as outlined in Table 6.4.8.

Table 6.4.8 Degree of Uncertainty for Main Variable Types

Type of Variable*	Degree of Uncertainty
Quote	± 10%
Known discount from low-volume quote	± 20%
Unknown discount from low-volume quote	± 30%
Material	± 10%
Uncertain equipment costs	± 20%

* More details about the variables are provided in Appendix 6.1.

The Department varied the inputs to the cost model according to the specified assumptions, as shown in Table 6.4.9. Minimum and maximum ranges are given to preserve manufacturer confidentiality.

Table 6.4.9 Manufacturing Parameter Ranges

Manufacturing Parameter	Min	Max	Unit
Equipment Uptime	0.8	0.9	%
Assembly Worker Downtime	0.16	0.24	%
Capital Recovery Rate	0.12	0.16	%
Auxiliary Equipment and Installation Cost	0.48	0.72	%
Building Depreciation Life	25	30	years
Tooling Depreciation	5	7	years
Ratio of Walkways to Fabrication and Storage	0.264	0.396	
Yearly Maintenance Ratio (% of Equipment Cost)	0.02	0.04	%
Utility Cost (% of Factory Cost)	0.024	0.036	%
Investment Relativity Factory	0.8	1.2	
Average Depreciation Life Factor	0.8	1.2	
Labor Rate Factor	0.8	1.2	
Benefits Ratio	0.3	0.4	%
Building Cost	50	150	$/sf
Space Overhead	0.2	0.3	%
Assembly Factor	1.2	1.8	
Ratio of Indirect-to-Direct Laborers*	0.1	0.2	
Management Span (People/manager)	20	30	
Pay Difference: Manager to Line Worker	0.8	1.2	

* "Table 6.4.6 refers to Direct to Indirect Labor Cost Ratio; and Table 6.4.9 refers to Direct to Indirect Labor Ratio (people); they are related by the weighted average cost/hour, utilization, etc. The former was used because it is more standard terminology in the industry; the latter was used because this is what is varied in the model."

Once it had set the ranges, DOE ran Monte Carlo simulations. To run a Monte Carlo simulation analysis, Crystal Ball selects inputs randomly according to the distributions, and tracks the effect on production costs. The result is a probability distribution for the production cost of each equipment sample. Rather than predicting a single production cost, the distribution describes the likelihood that the actual production cost is equal to a predicted value. Thus, DOE can quantify the uncertainty and variability in the production cost estimates. In general, the results were normally distributed. Figure 6.4.1 illustrates a typical Crystal Ball output.

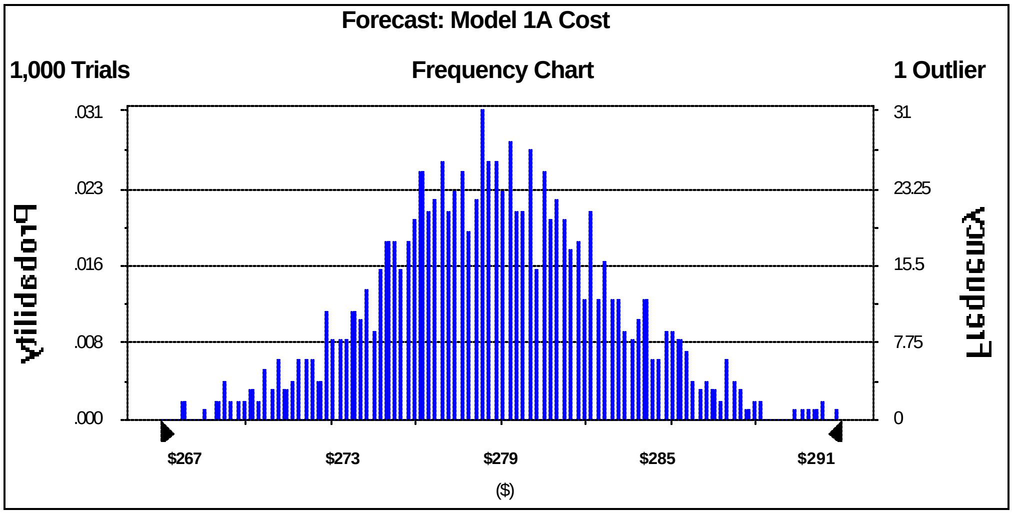

Figure 6.4.1 Probability Distribution for the Production Cost of an Equipment Sample

The Department ran several simulations for each product class. Figure 6.4.2 reports, for illustration purposes, the results of a sensitivity analysis of a sample Monte Carlo simulation on a model of non-weatherized gas furnaces. The tornado chart shows that the analysis is sensitive to base steel costs, labor-rate variations, and high-value components such as control boards, blower motors, and gas valves. Note that, in this case, cost is not so sensitive to production volume (i.e., for this unit, we are on a flat portion of a hypothetical production volume-versus-cost curve).

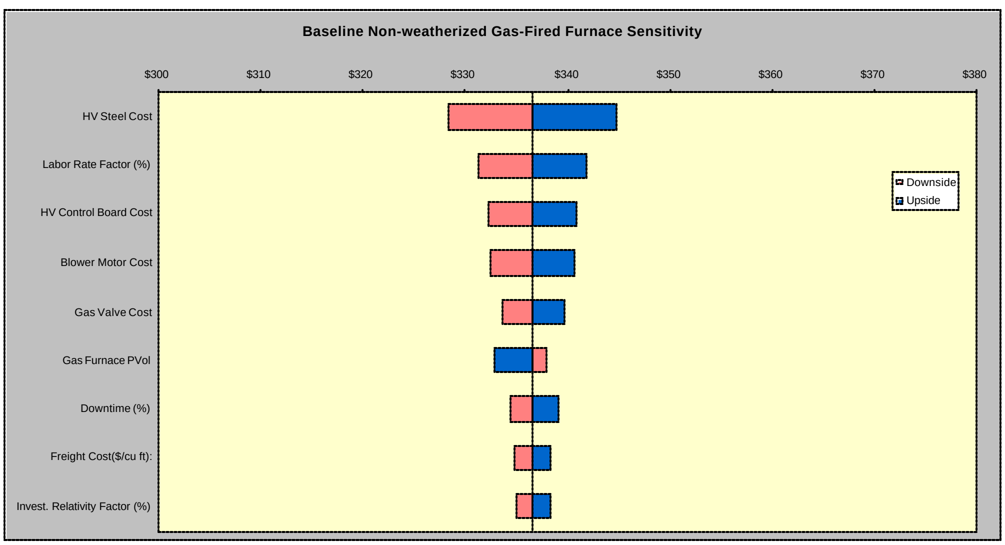

Figure 6.4.2 Importance of Input Parameters for Production Costs for Non-Weatherized Gas Furnaces

6.4.5 Curves of Manufacturing Cost Versus Efficiency

After generating each BOM for each theoretical and teardown unit and running the cost models with the appropriate assumptions, DOE gathered cost information for all product classes. The use of cost-per-pound estimates for boilers and mobile home furnace max-tech completed the process through which DOE generated the manufacturing costs. The Department then aggregated all of the available data to construct manufacturing costs-versus-efficiency curves (Figures 6.4.3 through 6.4.8).

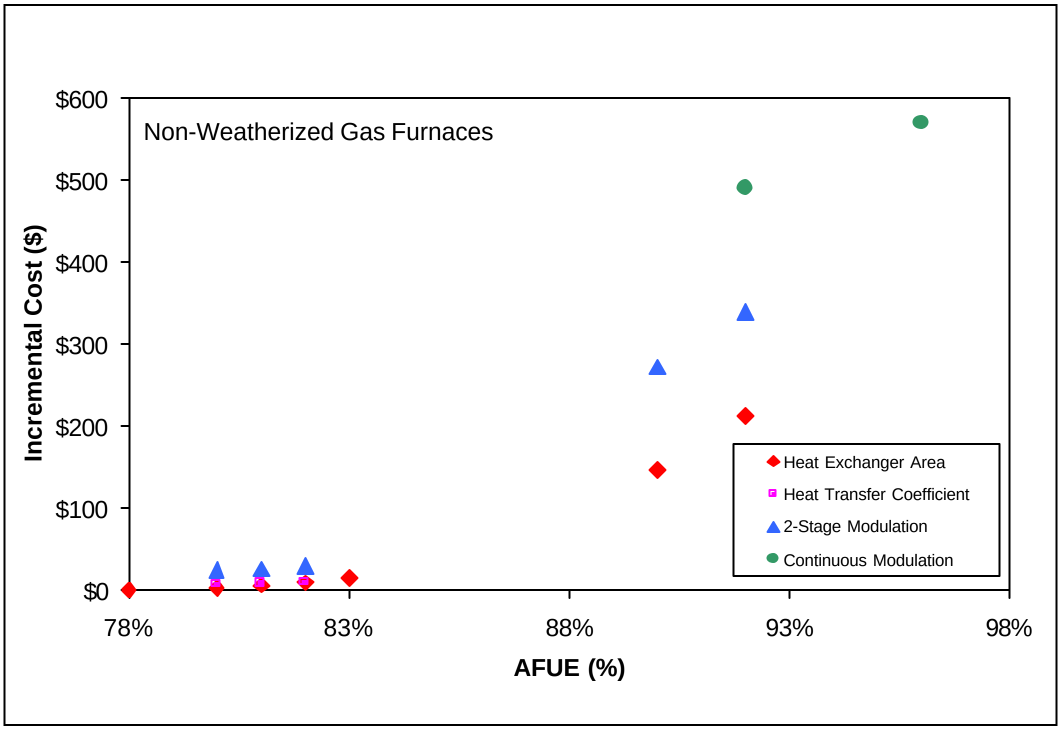

Figure 6.4.3 Incremental Manufacturing Costs for Non-Weatherized Gas Furnaces

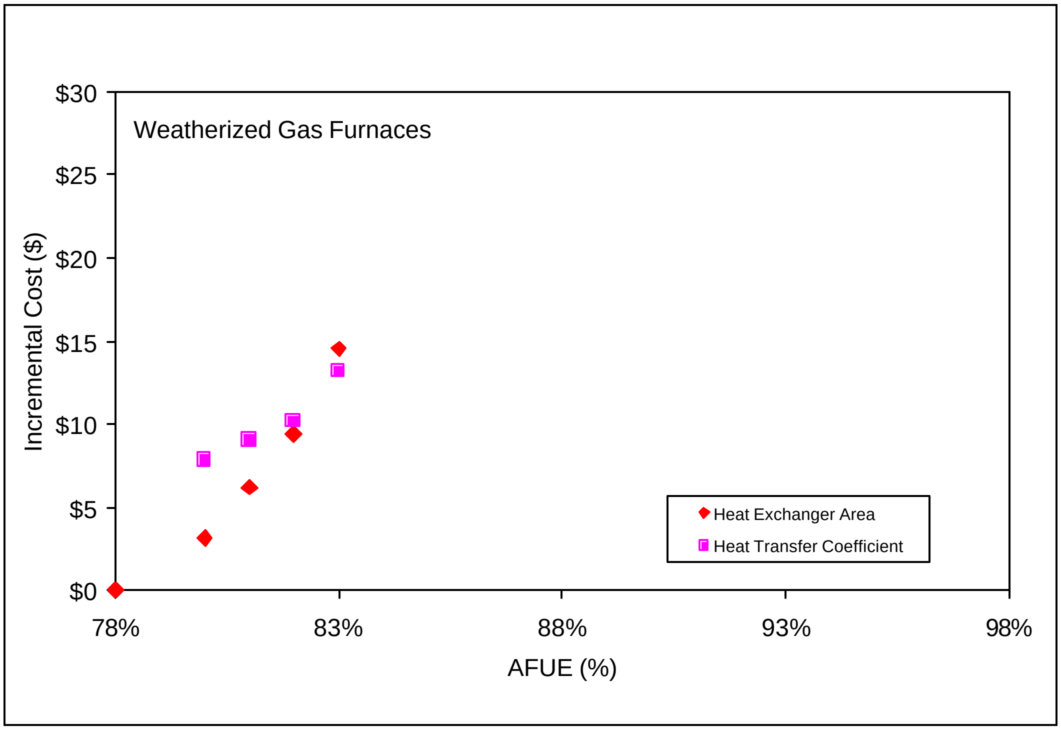

Figure 6.4.4 Incremental Manufacturing Costs of Weatherized Gas Furnaces

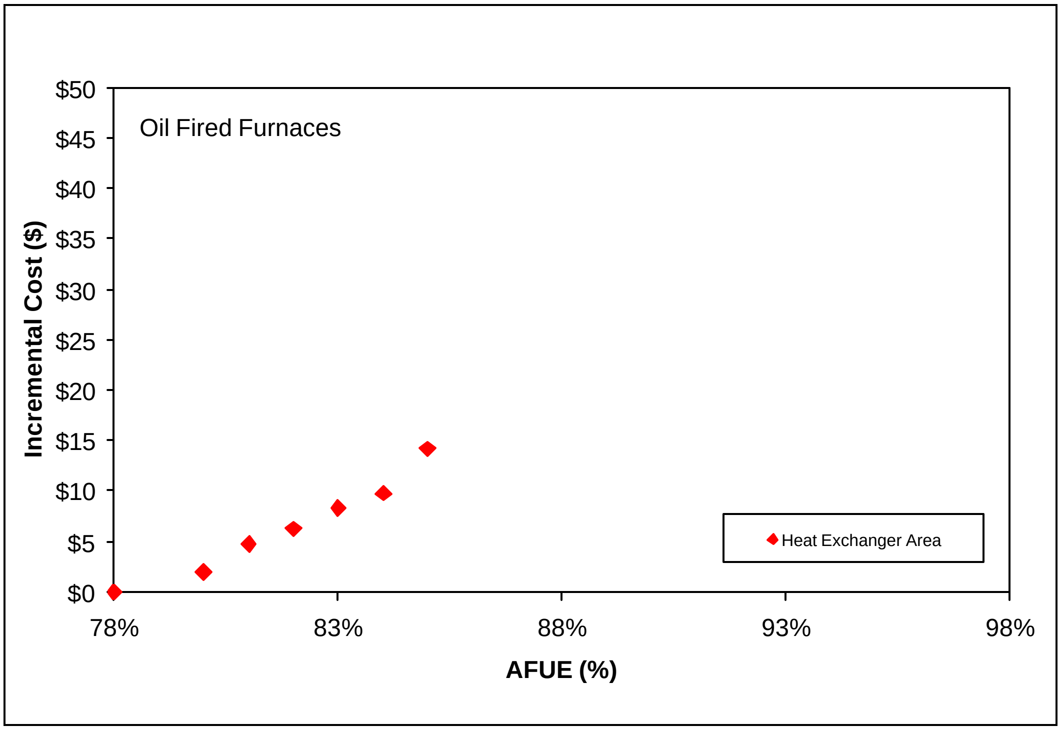

Figure 6.4.5 Incremental Manufacturing Costs for Oil-Fired Furnaces

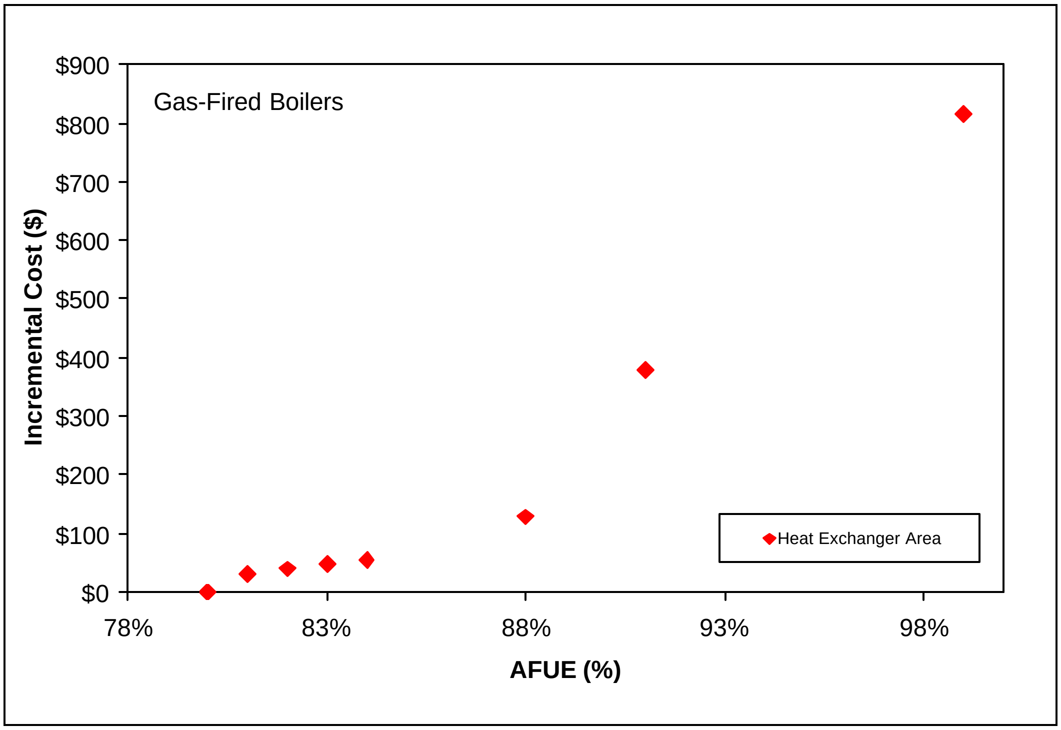

Figure 6.4.6 Incremental Manufacturing Costs for Gas-Fired Boilers

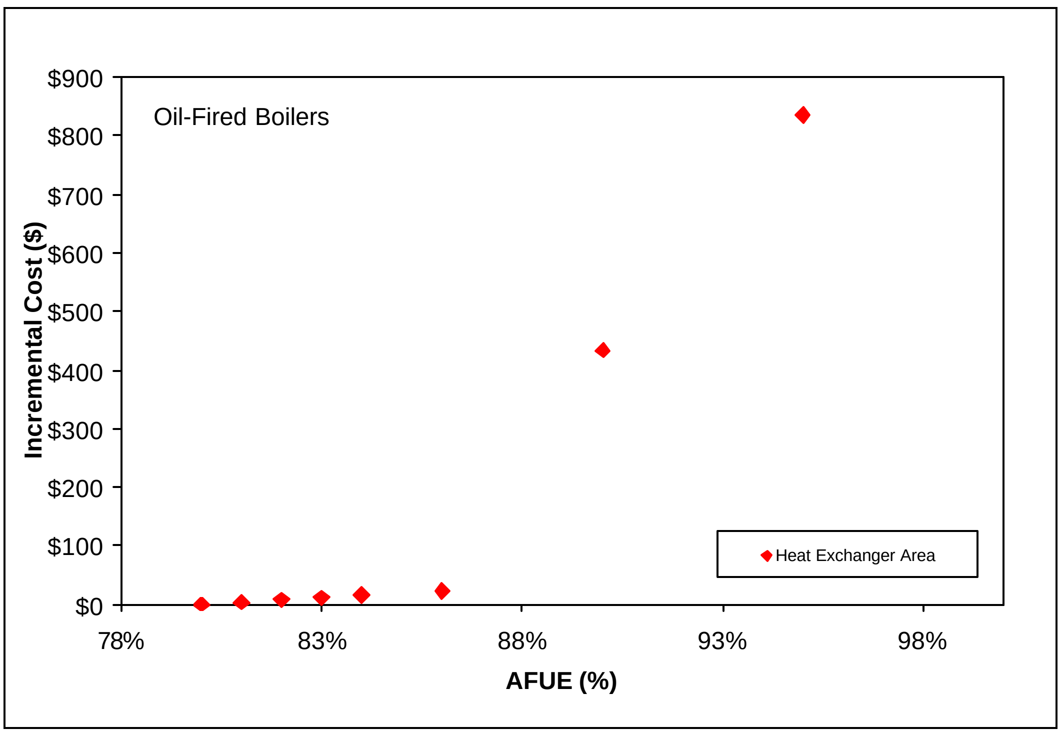

Figure 6.4.7 Incremental Manufacturing Costs for Oil-Fired Boilers

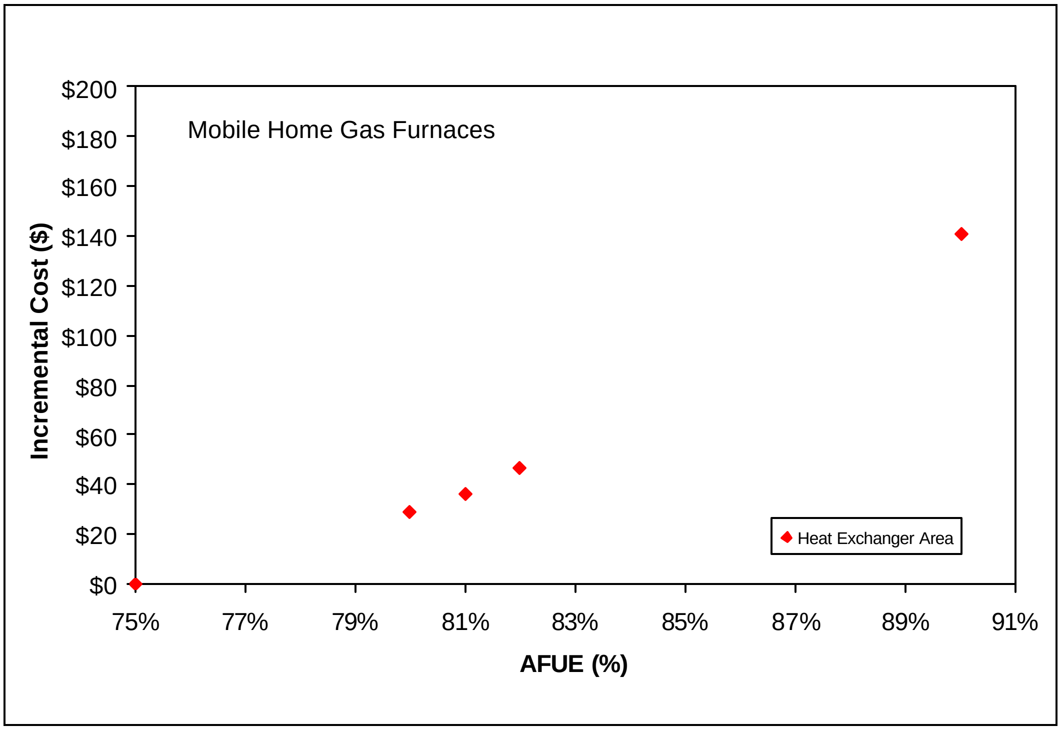

Figure 6.4.8 Incremental Manufacturing Costs of Mobile Home Gas Furnaces

6.5 INSTALLATION COSTS

The installation cost is the cost to the consumer for installing a furnace or a boiler; the Department does not consider it part of the retail price. The cost of installation covers all labor and material costs associated with the installation of a new unit or the replacement of an existing one. For furnaces and boilers, the installation cost is the largest single component of the total cost to the consumer. It is even larger than the equipment cost.

The predominant part of the installation cost is the venting system. The American National Standards Institute (ANSI) standard Z21.47-1993 defines four categories (I–IV) for gas-fired furnace or boiler venting systems. The categories are defined based on the operating pressure and temperature in the vent. Most non-condensing equipment operates with a Category I (high temperature, low pressure) venting system. Most condensing equipment operate with a Category IV (low temperature, high pressure) venting system, but some non-condensing boilers use a Category III (high temperature, high pressure) system.

For all product classes except weatherized gas furnaces and mobile home furnaces,[4] National Fuel Gas Code (NFGC) venting tables define the requirements for installing a Category I venting system. Installers install Category I venting systems according to the requirements in the NFGC venting tables.[5]

By investigating existing models and manufacturers' installation manuals, DOE determined that furnaces using a Category I venting system must utilize Type-B double-wall vent connectors in the venting system when an update from single-wall to double-wall vent connector is necessary. About two-thirds of installations incur this additional cost.

If the steady-state efficiency (SSE) of a non-condensing gas furnace exceeds 83 percent, it must be vented with a Category III system to prevent condensation problems. A Category III system is a venting system installed according to manufacturer specifications. It uses stainless steel material, and sealed joints.

The Department carried out a study to determine what fraction of installations at each efficiency level is likely to require a Category III venting system. Through this study, DOE produced a distribution of the difference between SSE and AFUE values, based on the models listed in the GAMA *Directory of Certified Efficiency Rating for Heating Equipment*.[6] The Department calculated SSE using furnace jacket losses reported from the test procedure[7] and took AFUE from the data in the GAMA directory. Knowing that the NFGC developed the venting tables for 83 percent SSE, and knowing the SSE-AFUE difference for the furnace models, the Department was able to estimate the fraction of models at each efficiency level that can be installed according to the NFGC venting tables requirements (Category I). The results indicate that the fraction of models that would require a

Category III venting system is 8 percent for 81 percent AFUE furnaces,[a] 35 percent for 82 percent AFUE furnaces, and 100 percent at 83–85 percent AFUE. Note that the percentage of actual furnace installations is expected to be somewhat different, since some models have higher level of sales than others.

For gas boilers, DOE applied the same methodology as for non-weatherized gas furnaces, except the SSE was shifted from 83 percent to 85 percent AFUE, due to the presence of isolated combustion in gas boilers and on/off time test differences. At 85 percent AFUE and above, DOE estimated that all installations would require Category III venting. Based on the results, no gas boilers below 85 percent AFUE would require Category III installation. However, to reflect actual construction practices, which require Category III venting for horizontally vented gas boilers,[8] DOE assumed that 20 percent of total gas boiler installations at 80 percent to 84 percent AFUE would require Category III venting.

For oil-fired appliances, DOE applied the same methodology as for non-weatherized gas furnaces and gas boilers, except the SSE was shifted from 83 percent to 85 percent for oil-fired furnaces and from 85 percent to 87 percent for oil-fired boilers, due to the decreased hydrogen content in oil fuel and lower stack losses in oil-fired appliances. During combustion, hydrogen combines with oxygen to form water, which leaves the system as vapor. Each pound of exiting water vapor represents a loss of about 1000 Btu. For both oil-fired product classes, DOE estimated that all installations at 85 percent AFUE and above would require Category III venting. Below 85 percent, no installations require Category III venting.

Table 6.5.1 summarizes the fraction of models estimated to require a Category III venting system for the applicable product classes. The Department applied these values in the engineering analysis.

[a] At present, two major manufacturers produce furnaces with efficiencies of 81 percent AFUE (using modulation technology) that can be installed with a Category I venting system.

Table 6.5.1 Fraction of Models Requiring a Category III Venting System

Class	AFUE					
	80%	**81%**	**82%**	**83%**	**84%**	**85%**
Non-Weatherized Gas Furnaces	0%	8%	35%	100%	100%	100%
Gas Boilers	20%	20%	20%	20%	20%	100%
Oil-fired Furnaces	0%	0%	0%	0%	0%	100%
Oil-fired Boilers	0%	0%	0%	0%	0%	100%

6.5.1 Data Sources

Because of the importance of installation cost, DOE devoted considerable effort to establishing appropriate installation costs to use in its analysis.

One source of data is a 1994 GRI report,[2] which GAMA supplemented in 2002 with an updated summary version of the data. The installation costs given in the GRI report were developed from the results of a field survey sponsored by several gas utilities and conducted in 1992. These data are relatively old and, particularly for condensing furnaces, may not represent a well-established market. Differences between new and replacement installation costs may be underestimated. Further, no detailed data are available from the report.

A second source is a 1999 Natural Resources Canada (NRCan) study that developed installation cost data for non-weatherized gas furnaces for four Canadian areas.[9] A company that provides cost estimates for building contractors conducted the study. The NRCan study provides the most current data set available, and the data are used by Canadian government agencies and are well documented. However, there are indications that, for condensing furnaces, these data are applicable only to installations in new construction.

The Department looked at other possible sources of installation costs, including data from Wisconsin from a 1999 survey of heating, ventilation, and air conditioning (HVAC) contractors.[10, 11] The Department did not use these data because of the very small size of the sample.

Because of the incomplete coverage of the above sets of data and the importance of installation costs to the analysis, the Department created a cost model based on the RS Means[12] construction-cost estimation method. Section 6.5.1.1 summarizes the model's critical assumptions and final results, and compares them to other available installation cost data sets. Appendix 6.2 documents all model calculations in detail, including results that are used as an input to the life-cycle cost (LCC) analysis.

6.5.1.1 Installation Model Approach

Applying the RS Means methodology to a furnace or boiler installation requires a detailed description of the equipment involved, including vent length, venting material, vent type, diameter, and number of elbows. To estimate these quantities, DOE reviewed relevant research results, data submitted as comments to DOE, and manufacturer installation manuals. The Department chose values representative for an average U.S. home, and described each assumption using a distribution of values derived from available data; DOE used a Crystal Ball Monte-Carlo simulation to model the resultant cost ranges.

Numerous installation configurations are possible, given site-specific venting conditions. The starting point for the model is the venting options detailed in the 1994 GRI report.[2] The Department modeled the most common installation configurations, including:

- New and replacement installations
- Single and multi-family dwellings
- Venting category: I (non-condensing), III (stainless vents), and IV (condensing)
- Vents: masonry chimneys, lined and un-lined, Type B metal or plastic PVC
- Vent connectors: single-wall and double-wall
- Water heater options: gas (vented in common w/furnace) and electric (isolated)
- Special situations: chimney relining[b] and orphaned water heaters[c]

For each appropriate combination of options, DOE created and costed a separate physical bill of materials. The Department then obtained the average cost for each efficiency level by weight-averaging the cost estimates of as many as 24 separate BOMs.

The weight-averaging used depends on how often each combination occurs in the field, as documented in the GRI report. Some circumstances have changed since the GRI survey was performed: Masonry chimneys have been relined in increasing numbers, and double-wall connectors are more commonly used. Therefore, DOE updated the GRI values based on recent installation trends.

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b Unlined masonry chimneys—an estimated 23 percent of the market in 2012— need to be relined 90 percent of the time to comply with the National Fuel Gas Code (source: NFGC and chimney size analysis, Appendix 6.2).

c If a furnace and gas water heater are commonly vented in a masonry chimney, and the furnace is replaced with a 90 percent+ AFUE unit, the water heater may be too small for the existing vent (orphaned). In this case, a relining or equivalent purchase of a new direct side-wall-vented water heater is necessary (source: NFGC analysis, Appendix 6.2).

Table 6.5.2 below summarizes DOE's estimates of the year 2012 market share of cost-significant options for non-weatherized gas furnaces.

Each installation option combination is associated with a physical BOM and vent configuration. For an individual BOM, the Department estimated the quantity of materials needed to install a gas furnace in an average U.S. home.[d] In the Monte Carlo simulation, installation size is varied to take into account large and small houses, apartment complexes, multiple-story dwellings, and furnace-size variations. The Department derived the ranges used from 1997 Residential Energy Consumption Survey (RECS) housing data and U.S. Census Statistics housing data.

Table 6.5.2 Installation Model, Non-Weatherized Gas Furnace Weighting Assumptions

Class	Variable	2012 Market Share	Source
Market	New Replacement	25% 75%	Residential Furnace and Boiler Market Analysis
Water Heater Options	Gas Common Vented Isolated Electric	50% 50%	1994 GRI survey confirmed by 2000 Water Heater rule
Vents	Unlined Masonry Lined Masonry Type B Metal Other	23% 27% 32% 18%	1992 GRI survey updated (Lined Masonry was 2%)
Vent Connector	Single Wall Double Wall Other	53% 36% 11%	1992 GRI survey updated (Single Wall was 73%)

Given a particular installation configuration and size, DOE created a BOM. The "master" BOM shown in Table 6.5.3 lists what DOE included in the cost estimates for all installation configurations. Items are turned on or off or multiplied by amount used, depending on the configuration. The BOM is a composite based on relevant trade literature, installation manuals, and furnace-installation-related line items found in RS Means (2003 Residential & Mechanical Cost Data).

[d] 1.6 story, 1,660 sf, with basement; 80 kBTU input furnace. (1997 RECS data, using non-weatherized gas furnace LCC subset, Ch.8).

Table 6.5.3 Master Bill of Materials for All Appliance Installation Configurations

Category	Item Description
Supply Gas Piping	One-foot section plus union to connect to existing piping
Ducting*	One return piece and one supply piece to connect to existing ductwork
Furnace Installation	Gas furnace—site and connect; if replacement, includes removal
Electrical Hookup	New or replacement thermostat + wiring—site and connect
Vent Installation	Type B metal vent, stainless vent, chase with liner,** or plastic vent
Vent Connector	Single or double wall
Relining (if necessary)	Flexible two-ply aluminum liner w/connections
Water Heater Vent (if present)	Single or double-wall vent connector, or direct water-heater vent cost (if present)
Drainage (if present)	Condensate hose, and pump (if necessary)

* Indirect materials—sealants, fasteners, etc.—are assumed to be part of overhead and are excluded.

** Newly constructed masonry chimneys use a wooden chase with a two-ply flexible chimney liner and brick facade.

Finally, the Department calculated costs for individual BOM line items using the material and labor assumptions listed in Table 6.5.4.

Table 6.5.4 Material and Labor Cost Assumptions

Type	Assumption	Source
Material	List Price – 25% (low volume contractor discount) + 10% contractor markup	McMaster, Grainger, and vent material supplier quotes
Labor	49 $/Hour Crew Rates	US Average, 2003 RS Means
	Crew Labor Time	RS Means, with proxy substitutions

6.5.1.2 Installation Model Results

The Department obtained the total cost for each efficiency level by weight-averaging cost estimates for 24 separate BOMs. For the five efficiency levels considered (80 percent, 81 percent, 82 percent, 83 percent, and 90 percent), the total number of BOMs was 96.[e] Because some venting configurations are equivalent to others, the model costs a total of 58 separate BOMs to account for all common venting configuration combinations. Table 6.5.5 shows the results of these combinations for non-weatherized gas furnaces in an average U.S. home.

Table 6.5.5 Non-Weatherized Gas Furnace, Installation Results

Type	AFUE	Weighted Average Cost ($)**	Incremental Installation Cost* ($)
Non-Condensing	78%	738	--
	80%	742	4
	81%A: Two-stage Modulation	772	34
Near-Condensing	81%B: 8% Stainless Vent	818	80
	82%: 40% Stainless Vent	983	245
	83%: 100% Stainless Vent	1,377	639
Condensing	90%+ Plastic Vent	995	257

* Relative to 78%-AFUE furnace

** The costs shown are in $2002 to coincide with the Installation model estimates

6.5.1.3 Model Results Compared to Other Data

Table 6.5.6 shows a detailed comparison of the Installation Model results with the GRI, Canadian, and Wisconsin installation cost data sets for 80 percent AFUE and 90 percent AFUE efficiency levels for non-weatherized gas furnaces. Installation cost estimates vary significantly, explained to a large extent by differences in methodology, sampling error, and assumptions. In particular, assumptions for the 80 percent AFUE furnace can differ depending on what is, or is not, included in an installation. The following sections explore and attempt to reconcile these differences.

[e] The two 81 percent cases and the 82 percent and 83 percent cases differ only in the fraction of installations requiring Category III venting systems.

Table 6.5.6 Comparison of Installation Model, GRI, NRCanada, and Wisconsin Costs

	Installation Model*			**GRI****	**NR Can****	**Wisconsin****
	Replacement ($)	New ($)	Avg_{wtd} ($)	Replacement ($)	Avg_{wtd} ($)	Avg_{wtd} ($)
80% Non-condensing	739	1,105	831	965	371	668
90%+ Condensing	1,053	967	1,032	1,239	401	908

* The costs shown reflect weighting of venting installation cases given in the 1994 GRI report (for comparison), and these are not comparable with the data in Table 6.5.5.

** Adjusted to 2001 $ using Consumer Price Index (CPI) for comparison.

Comparison of Installation Model to GRI Estimates. There are a number of possible reasons for the observed differences in 80 percent AFUE installation cost between the Installation Model and GRI data. These include:

1. Furnace relining and vent connector costs are weighted differently for the 80 percent AFUE case. GRI applies a cost for relining plus Type B vent connector (15 percent of the time), while the Installation Model applies a cost for relining plus Type B vent connector (23 percent of the time).
2. Non-efficiency related costs may differ – i.e., the GRI survey may include more ductwork or plumbing labor than is assumed in the Installation Model.
3. Labor costs may have declined in real terms between 1992 and 2001.

For the 90 percent AFUE level, focusing on incremental costs instead of total installation costs mitigates the impact of the factors described above. As shown in Table 6.5.7, for the replacement market, the Installation Model and GRI agree to within 13 percent — $314 versus $274. For the new construction market, there is a sharp difference. The Installation Model predicts that the installation cost of a 90 percent AFUE condensing furnace will be less than that of an 80 percent AFUE non-condensing unit, since the plastic pipe vent of the condensing furnace costs less than a Type B metal chimney. GRI assumes in its *New House Usage Analysis* that new construction furnace installation costs are equivalent to replacement installation costs (assuming a vent already exists).

Table 6.5.7 Comparison of Incremental Installation Cost for 90 percent AFUE Furnace

		Incremental Cost Relative to 80% AFUE Furnace ($)
Installation Model (2002)*	Replacement	314
	New	-138
	Avg_{wtd}	201
GRI (1992)**	Replacement and New	274
Wisconsin (1996)**	Avg_{wtd}	239

* The costs shown reflects weighting of venting installation cases given in the 1994 GRI report (for comparison).

** Adjusted to 2001 $ using CPI Index for comparison.

Comparison of Installation Model to NRCanada Estimates. From discussions with Helyar & Associates, who conducted the Canadian cost survey, DOE understands that the Canadian data are valid only for the case of a condensing unit being installed into new construction. The Canadian estimates do not include gas piping, electrical hookup, or removal of an old furnace. The 80 percent AFUE Canadian estimates also do not include relining or vent connector costs for replacement installations, or the cost of a new metal vent for new installations (they assume a power-vented plastic vent for 80 percent AFUE). For the 90 percent AFUE condensing furnace, Canadian estimates do not include provision for a condensate pump (assumes a drain will be available in new constructions).

With the above assumptions incorporated, the Installation Model estimates costs of a condensing furnace in new construction that are comparable to the Canadian data. The model estimates an average cost of $463, compared to $401 for the Canadian data (agreement within 15 percent).

Comparison of Installation Model to Wisconsin Estimates. The Wisconsin installation data consist of a sample of ten condensing-furnace installations performed in Wisconsin. A comparison shows absolute costs of $831 (Installation Model) versus $668[f] (Wisconsin) for 80 percent AFUE, and $1032 versus $908 for 90 percent AFUE condensing. The explanations for cost differences discussed above apply; in addition, the Wisconsin data implicitly assume regional weightings of vent-connector type, vent type, and gas-to-electric water heater ratio. The Installation Model uses national averages that may be different from the Wisconsin custom, with as large as a +/- $75 cost impact (see Appendix 6.2).

[f] $668 is based on a very limited sample. Note that in Wisconsin the non-condensing furnace installations represent less than 15 percent of the installations.

The incremental cost difference for a 90 percent-AFUE furnace is $201 (Installation Model) versus $239 (Wisconsin), showing agreement within 15 percent.

Comparison Summary. In summary, DOE found that available data sources were in reasonable agreement with its cost model when the installation costs were compared using similar assumptions. For the 90 percent condensing candidate standard level, the Installation Model incremental costs match GRI costs within 13 percent for replacement markets, and match Wisconsin costs within 15 percent for all markets. The Canadian data do not directly apply to the Unites States, but when similar assumptions are used, the Installation Model agrees with Canadian installation costs within 15 percent.

6.5.2 Non-Weatherized Gas Furnaces

For non-weatherized gas furnaces, DOE considered the data derived with the Installation Model as the most current and comprehensive available for the analysis, and used the other sets of data to provide a basis for bounding scenario analysis.

The Department determined that there is a small additional installation cost for an 80 percent AFUE furnace relative to a baseline model (78 percent AFUE) furnace. This cost involves the need to reline some masonry chimneys and applies to single-stage as well as modulating furnaces.

For the 81 percent AFUE level, DOE considered two cases for installation cost. The first assumes that no installations would require a Category III venting system, reflecting use of two-stage modulation technology. At present, two major manufacturers produce furnaces with 81 percent AFUE using modulation technology that can be installed with a Category I venting system. By investigating existing models and manufacturers' installation manuals, DOE determined that these furnaces must utilize Type B double-wall vent connectors in the venting system.

The second case assumes use of single-stage furnaces. In this case, DOE assumed that 8 percent of installations would require a Category III stainless-steel vent to ensure safe operation. The remaining 92 percent would need to utilize Type B double-wall vent connectors in the venting system.

To estimate the costs of Category III venting systems (for 81 percent, 82 percent, and 83 percent AFUE), DOE applied Installation Model costs ($688) for both the Installation Model and NRCanada columns in Table 6.5.8. For the GRI column, DOE applied the installation cost for a Category III venting system from the GRI study ($1,767). Reasons for the cost difference include a larger market and higher sales volumes today compared to 1992, greater availability (leading to lower cost) of the specialized steel used in these systems, and possible differences in vent length assumptions.

For the 82 percent and 83 percent AFUE levels, DOE determined that 35 percent and 100 percent, respectively, of units (single-stage and modulating) could be above 83 percent SSE, and these units would require a Category III venting system for safe operation.

Condensing furnaces at 90 percent AFUE use a Category IV venting system, which is mostly composed of a side-wall venting system with plastic vent pipes. Each of the installation cost data sources provides installation cost data for condensing gas furnaces; most account for the installation of a new vent system, resizing of the remaining common system, condensate neutralization, and condensate pumping for disposal. The Department assumed that installation costs for all condensing furnaces are similar, since available information suggests that efficiency levels higher than 90 percent do not appreciably affect the total installation cost for condensing gas furnaces.

Table 6.5.8 presents the installation cost for non-weatherized gas furnaces, based on the different data sources. The cost data are presented in 2001 dollars to coincide with the manufacturing cost estimates.

Table 6.5.8 Installation Cost for Non-Weatherized Gas Furnaces ($)

Efficiency Level (AFUE)	**NRCan (US $)**	**Installation Model (US $)**	**GRI (US $)**
78% - Baseline Model	382	727	773
80%	382	731	965
81%- two-stage, no Category III	382	760	965
81%- single-stage, 8% Category III	432	810	1,104
82%	634	1,012	1,671
83%	1,012	1,356	2,732
90%	411	980	1,239
93% and above	411	980	1,268

6.5.3 Weatherized Gas Furnaces

Weatherized gas furnaces are typically sold in "packaged units" together with an air conditioner, and are usually installed outside. The unit vents flue gases directly into the surrounding air.

When installing the entire packaged unit, it is difficult to separate the installation cost of the heating section from the installation cost of the cooling section. The installation cost accounts for the installation of the equipment because the venting system is an integral part of the equipment.

The Department estimated the installation cost for the baseline model weatherized gas furnace using data from Section 400 of RSMeans Mechanical Cost Data.[12] It based the cost estimate on hours and hourly rates. Table 6.5.9 shows the details of the approach DOE used to estimate the installation cost.

Table 6.5.9 Installation Cost for Weatherized Gas Furnaces

Major Unit	Line #	Cooling/Heating Capacity	Crew	Cost per hr	Daily Crew Output	Person-Hours	Total Cost
400	1100	36 kBtu/hr and 60	Q–5	$49.13	0.7	22.86	$1,123

The estimated total installation cost is $1,123. Although limited data were available, the assumption that installation cost remains mostly constant as efficiency increases seems to be reasonable for single-package systems. The increases in size and weight for more-efficient single package systems are relatively small relative to the large size and weight of the baseline model unit.

6.5.4 Mobile Home Gas Furnaces

For mobile home gas furnaces, installation costs are part of the equipment cost because mobile home gas furnaces are assembled in the factory rather than in the field. The manufacturer's markup includes these baseline model factory assembly costs. For 90 percent+AFUE condensing furnaces, there is an additional installation cost of $181 to account for condensate disposal systems.

6.5.5 Oil-Fired Furnaces

The Department modified the Installation Model to estimate venting costs for oil-fired furnaces. These modifications include:

1. Regional weighting was changed for vent connector type, vent type, and percentage of water heaters vented in common from a national 2012 projection to a Northeast 2012 projection.
2. New/Replacement market weighting was changed from 25 percent/75 percent to 5 percent/95 percent.
3. Vent and vent connector diameters were increased by 1 inch to allow for larger capacity flows (based on installation manual reviews).
4. Appliance capacity was shifted to reflect 1997 RECS data and larger size equipment.
5. Type L stainless steel relinings must be applied 100 percent of the time according to National Fire Protection Association (NFPA) 31, section 6.5.5, 2001 Edition.

6. Type L vents must be used rather than Type B.

With these modifications, the Installation Model results for oil-fired furnaces are shown in Table 6.5.10. The cost data are presented in 2001 dollars to be on the same time-frame basis as the manufacturing cost estimates.

Table 6.5.10 Installation Cost for Oil-Fired Furnaces

Type	AFUE	Weighted Average Cost ($)	Incremental Installation Cost ($)
Non-Condensing	80%-83%	751	--
Near Condensing	84%-85%: 100% Category III	1641	890

6.5.6 Hot-Water Gas Boilers

The Installation Model was also modified to estimate venting costs for hot-water gas boilers. Modifications (from the non-weatherized gas furnace approach) include:

1. Regional weighting was changed for vent connector type, vent type, and percentage of water heaters vented in common from a national 2012 projection to a 15 percent Midwest/15 percent Northwest/70 percent Northeast 2012 projection.
2. New/Replacement market weighting was changed from 25 percent/75 percent to 5 percent/95 percent.
3. Vent and vent connector diameters were increased by 1 inch to allow for larger capacity flows (based on installation manual reviews).
4. Appliance capacity was shifted to reflect 1997 RECS data and larger size equipment.
5. Labor times for gas boilers, as listed in RS Means, are too high when compared to oil boilers and oil furnaces, per conversations with the RS Means Co. On June 11, 2003. As a proxy, oil boiler installation times are used. RS Means is reviewing the numbers and will issue a correction in the distant future.

With these modifications, the Installation Model results for gas boilers are shown in Table 6.5.11. The cost includes the DOE assumption that in the 80-84 AFUE percent range, 20 percent of the installations will require a Category III vent. This assumption reflects the practice that when the installer uses a sidewall vent, and this vent is more than 45° from vertical, then a Category III vent is required. The cost data are presented in 2001 dollars to be on the same time-frame basis as the manufacturing cost estimates.

Table 6.5.11 Installation Cost for Hot-Water Gas Boilers

Type	AFUE	Weighted Average Cost ($)	Incremental Installation Cost ($)
Non-Condensing	80-84%	1,679	--
Near Condensing	85-88%: 100% Category III	2,833	1,154
Condensing	90%	2,091	412

6.5.7 Hot-Water Oil-fired Boilers

The Installation Model was modified to estimate venting costs for hot-water oil boilers. These modifications include:

1. Regional weighting was changed for vent connector type, vent type, and percentage of water heaters vented in common from a national 2012 projection to a Northeast 2012 projection.
2. New/Replacement market weighting was changed from 25 percent/75 percent to 5 percent/95 percent.
3. Vent and vent connector diameters were increased by 1 inch to allow for larger capacity flows (based on installation manual reviews).
4. Appliance capacity was shifted to reflect 1997 RECS data and larger size equipment.
5. Type L stainless steel relinings must be applied 100 percent of the time (NFPA 31, section 6.5.5, 2001 Edition).
6. Type L vents must be used rather than Type B.

With these modifications, the Installation Model results for hot-water oil boilers are shown in Table 6.5.12.

Table 6.5.12 Installation Cost for Hot-Water Oil-fired Boilers

Type	AFUE	Weighted Average Cost ($)	Incremental Installation Cost ($)
Non-Condensing	80-84%	$1,631	--
Near Condensing	85-88%	$2,556	$925
	90%+	$2,091	$460

6.6 MAINTENANCE COST

The maintenance cost ($/year) includes regular maintenance and repair of a furnace or a boiler when it fails. This cost covers all associated labor and material costs.

For non-weatherized and weatherized gas furnaces and gas boilers, DOE used the maintenance cost data provided in the 1994 GRI report.[2] The costs reported in this study derive from a field survey sponsored by several gas utilities that repair and service furnace and boiler equipment. The survey methodology estimated the average cost per service call as the average total service charge (parts, labor, other charges).

For non-weatherized gas furnaces, the average total service charge is $183. The GRI study also characterized maintenance frequency as a function of the equipment efficiency level: once every four years for 80–81 percent AFUE equipment and once every three years for 82–83 percent AFUE equipment. For 90 percent and 92 percent AFUE, the value represents a service contract that includes a specified set of routine repairs. The 96 percent AFUE furnace also includes a service contract that provided for regular annual maintenance. The Department annualized the costs over the estimated furnace lifetime (Table 6.6.1).

Table 6.6.1 Annualized Maintenance Cost for Non-Weatherized Gas Furnaces

AFUE	Mean
81% and less	$35
82-83%	$58
90% and 92%	$61
96%	$102

For oil-fired furnaces and oil-fired boilers, DOE applied the results of a survey performed for its previous water heater rulemaking.[13] This survey identifies the typical cost of annual service contracts applied to all oil equipment in a house. These contracts are very common in the Northeast, where most of the oil heating equipment is located. The mean cost of the annual contract is $104.

For mobile home furnaces, DOE used the results from the 1993 DOE rulemaking for this product class.[14] This study found an average annual maintenance cost for mobile home furnaces of $41. It also identified the additional maintenance cost required for design options such as increased heat transfer area and two-stage modulation.

6.7 ENGINEERING ANALYSIS PAYBACK PERIODS

This section describes the calculation of simple payback periods for each design option for each product class. For a given design option, the payback period expresses the amount of time required for the cumulative savings in energy cost to equal the incremental cost to the consumer of purchasing a particular design (relative to the baseline model technology in each instance). The Department calculated the payback period for each design option relative to the baseline model design according to the following relationship:

$$PAYBACK = \frac{\Delta CC}{\Delta OC} = \frac{\Delta RC + \Delta IC}{\Delta EC + \Delta MC}$$

where:

$PAYBACK$	= payback period (years);
ΔCC	= change in consumer first cost relative to baseline model ($),
ΔOC	= change in operating cost relative to baseline model ($/yr),
ΔRC	= change in retail cost relative to baseline model ($/yr),
ΔIC	= change in installation cost relative to baseline model ($),
ΔEC	= change in first-year energy cost relative to baseline model ($/yr), and
ΔMC	= change in annualized maintenance cost relative to baseline model ($/yr).

The Department based the energy cost on energy consumption calculated according to the DOE test procedure for furnaces and boilers.

Although the LCC Analysis yields a more definitive understanding of the economic impact of the design options for consumers, the payback periods reported here provide a preliminary indication of how the options rank. The Department presents these payback periods in order to address the legally established “rebuttable” payback period, as calculated under the applicable test procedure. (42 U.S.C. 6295 (o)(2)(B)(iii))

6.7.1 Calculation of Fuel Consumption for Each Design Option

The calculation of fuel cost for each fuel-efficiency option begins with the fuel consumption of the baseline model in each product class. The Department constructed alternative design options to yield progressively higher AFUE levels. The Department considered several design options for reaching each specific AFUE level above the baseline model, as shown in Table 6.7.1.

Table 6.7.1 Fuel-Efficiency Design Options

Product Class	Increased HX Area	Improved Heat Transfer Coefficient	2-stage Modulation	Step Modulation
Non-Weatherized Gas Furnaces: 80% AFUE	X	X		
Non-Weatherized Gas Furnaces: 81-83% AFUE	X	X	X	
Non-Weatherized Gas Furnaces: Condensing	X		X	X
Weatherized Gas Furnaces	X			
Mobile Home Gas Furnaces	X			
Oil-Fired Furnaces	X			
Hot-Water Gas Boilers		X		
Hot-Water Oil-Fired Boilers	X	X		

The Department calculated fuel consumption based on the method for calculating annual fuel energy use described in the DOE test procedure for furnaces and boilers. The details are reported in Appendix 6.3.

6.7.2 Calculation of Electricity Consumption

The Department has determined that it does not have the authority to regulate electricity consumption in residential furnaces and boilers. However, some design options (i.e. modulation) affect both fuel and electricity consumption of the appliance; therefore electricity consumption is calculated for completeness and accuracy. The electricity consumption of residential furnaces and boilers is represented by the annual auxiliary electrical energy (E_{AE}) parameter, which DOE calculated and reported in kWh/yr in accordance with the DOE test procedure, paragraph 10.2.3.[15] The details of the approach to calculate electricity consumption are reported in Appendix 6.3. The E_{AE} parameter does not include blower operation for the air conditioner during the cooling season.

6.7.3 Derivation of Fuel Costs

The Department derived annual fuel costs from fuel consumption, based on residential prices of $7.56/million Btu (MMBtu) for natural gas and $8.11/MMBtu for residential oil. It derived annual electricity costs based on a residential price of $0.0768/kWh. These are the forecast values for 2012 from the Energy Information Administration's *Annual Energy Outlook 2003*.[16]

6.7.4 Rebuttable Payback

Section 325(o)(2)(B)(iii) of the Act, 42 U.S.C. 6295(o)(2)(B)(iii), establishes a rebuttable presumption that a standard is economically justified if the Secretary finds that ‘‘the additional cost to the consumer of purchasing a product complying with an energy conservation standard level will be less than three times the value of the energy. . . savings during the first year that the consumer will receive as a result of the standard, as calculated under the applicable test procedure . . . . ’’

To satisfy statutory rebuttable payback requirements, DOE calculated payback periods using the laboratory-based DOE test procedure. The tables presented in Appendix 6.4 provide detailed results for each option and depict the relationship between the payback period and various design options for each product class.

The payback periods for some efficiency levels can not be accurately established due to discrepancies in the algorithm for calculating the energy use in the current furnace/boiler test procedure. The energy consumption as calculated in the test procedure depends indirectly on the design heating requirement (DHR) parameter. In the current test procedure, DHR is a step function of furnace output capacity ranges Q_{OUT}. The Department observed that small changes in Q_{OUT} may assign an efficiency level to a different DHR range, with the result that more-efficient designs (at higher AFUE) may use more energy than designs represented by a lower AFUE level. Therefore, in these cases the calculation of payback period yields a negative value, because the term ΔEC (change in energy cost relative to baseline model) is negative. More details about this discrepancy are provided in section 6.3.2.3 of Appendix 6.3.

6.7.4.1 Rebuttable Payback Results

Using the cost inputs described above, combined with energy calculations per the DOE test procedure, the Department calculated simple payback periods for each efficiency level using the ratio of incremental total installed cost to the change in the annual operating cost (see Table 6.7.2). A number of efficiency levels higher than current standards satisfy the rebuttable payback requirements by this metric. Note that in the process of setting a standard, the Department weighs many factors in addition to the economic justification. (42 U.S.C. 6295(o)(2)(B)(i))

Table 6.7.2 Efficiency Levels with Less Than 3-year Payback Period Using DOE Test Procedure

Product Class	**Efficiency Level (AFUE)**	**Payback (years)**
Non-weatherized Gas Furnace	80%	1.0
Weatherized Gas Furnaces	80%	0.6
	81%	0.8
	82%	0.9
Mobile Home Furnaces	80%	2.8
Oil-fired Furnaces	80%	0.2
	81%	0.2
	82%	0.2
	83%	0.3
Hot-Water Oil-fired Boilers	81%	0.4
	82%	0.4
	83%	0.4
	84%	0.4

For non-weatherized gas furnaces, the 80 percent AFUE furnace show a payback period of 1 year. This design level is the only one for this product class to show a payback period of less than 3 years. For weatherized gas furnaces, the 80, 81 and 82 percent AFUE furnaces shows payback periods of less than 1 year. For mobile home gas furnaces, the payback period for the 80 percent AFUE furnace is 2.8 years. For oil-fired furnaces, the 80, 81, 82 and 83 percent AFUE furnaces show payback periods of 0.2 - 0.3 years. There is no efficiency level for hot-water gas boilers which shows a payback period of less than 3 years. Therefore no design option satisfies the rebutable payback assumptions for this product class. For hot-water oil-fired boilers, the payback period is 0.4 years for efficiency up to 84 percent AFUE.

The Department based all of the above payback periods on energy consumption according to the DOE test procedure. Payback periods calculated based on energy consumption in actual field conditions may differ significantly. The latter considerations are addressed in the LCC analysis, see Chapter 8 for further details.

6.8 ENGINEERING SPREADSHEETS

The spreadsheet containing the calculations for the engineering analysis for all product classes is posted on the DOE web site. It contains an introductory worksheet that guides the user. The spreadsheet tool containing the Installation Model is posted on the DOE website at: http://www.eere.energy.gov/buildings/appliance_standards/residential/furnaces_boilers.html. It contains a text file that guides the user how to install and to use the tool.

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